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Generation of tunable narrowband laser pulses in the ultraviolet with a pulsed dye amplifier seeded by a near-infrared diode laser

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Abstract

We demonstrate the generation of narrowband laser pulses in the ultraviolet (UV) region with a continuous tunability over 10 GHz. To realize such pulses we construct a four-pass pulsed dye amplifier with an external cavity diode laser (ECDL) at the near-infrared (NIR) region as a seed laser, and do the frequency doubling. The achieved pulse energy is about 10 μJ at 369.4 nm with a 230±20 MHz bandwidth and 3.3±0.2 ns pulse duration.

Keywords: diode laser, pulsed amplification, nanosecond UV laser

1. Introduction

Tunable narrowband pulsed lasers are of great need in atomic and molecular physics. For our case at hand, we need such pulses to carry out spectroscopic studies of Yb^+ ions under natural abundance (which contain $^{170-175}$Yb with comparable existing ratios) by resolving hyperfine structures [1]. The transition wavelength of Yb^+ $6s_{1/2} - 6p_{1/2}$ is 369.4 nm which is in the UV region. Because of the presence of several different isotopes of Yb, the UV light source we need at this wavelength must be tunable over several GHz.

To achieve such tunable narrowband pulsed lasers in the UV region, we construct a pulsed dye amplifier with a tunable narrowband cw laser as a seed. Since commercial cw lasers in the UV region with required specs are not available, we choose a cw laser in the NIR region (369.4×2=738.8 nm) as a seed laser, and do the frequency-doubling after the amplification. Although various kinds of high-gain amplifiers with cw seed lasers have been developed over the last two decades, which include commonly used single-cuvette multi-pass dye amplifiers [2–9], multi-pass dye jet amplifiers [10] and multi-stage sequential amplifiers [11], we find similar amplifiers in neither NIR nor UV regions.

To start the present work, we first tried a commercial Ti:Sapphire ring laser (Coherent 899, pumped by solid-sate laser) with > 100 mW output power as a seed laser. To amplify the seed laser, however, we have encountered serious problems due to the pointing instability of the seed laser, and eventually gave up. Instead, we have employed an ECDL, which has a much lower output power (maximum 15 mW at 738.8 nm) but far better pointing stability. The ECDL has neither long-term nor short-term pointing drift as long as the lasing is well-established at the fixed laser wavelength. In contrast the lasing in the ring laser is very fragile and requires frequent realignments of the optical components to maintain the lasing, which results in a different pointing of the output. In the worst case, the change of the pointing of laser output can be of the order of ~ 0.1 degree, which leads to the millimeter - centimeter shift of the beam position after the propagation of several meters. Related to the present work, we note that a multi-pass dye amplifier with a diode laser (without external cavity) in the visible region has already been demonstrated [6], but the linewidth of the amplified pulses is rather broad (~ 0.5 GHz) for 5 ns pulses because of the absence of the external cavity for the seed laser.

In this paper, we demonstrate a tunable four-pass narrowband dye amplifier with an ECDL at 738.8 nm as a seed laser. Obtained pulses at 369.4 nm have a pulse energy of 10 μJ with a 230±20 MHz bandwidth and 3.3±0.2 ns pulse duration after the frequency-doubling by the nonlinear crystal, and the tunability is as much as 10 GHz.

2. Experiment

The experimental setup of our amplifier is shown in Fig. 1. The seed source is an ECDL (DL100, Toptica) tuned at the central wavelength of 738 nm with maximum 15 mW cw output power. The linewidth of the ECDL is as narrow as < 1 MHz if the integration time of the measurement is 5 μs. An optical isolator is installed just at the output port of the ECDL to prevent the backward propagating amplified spontaneous emissions (ASE) from injecting into the diode and causing damage and/or mode hopping. After the isolator, half of the total output power is taken by a half-mirror for other purposes such as the wavelength measurement. A pair of cylindrical lenses of

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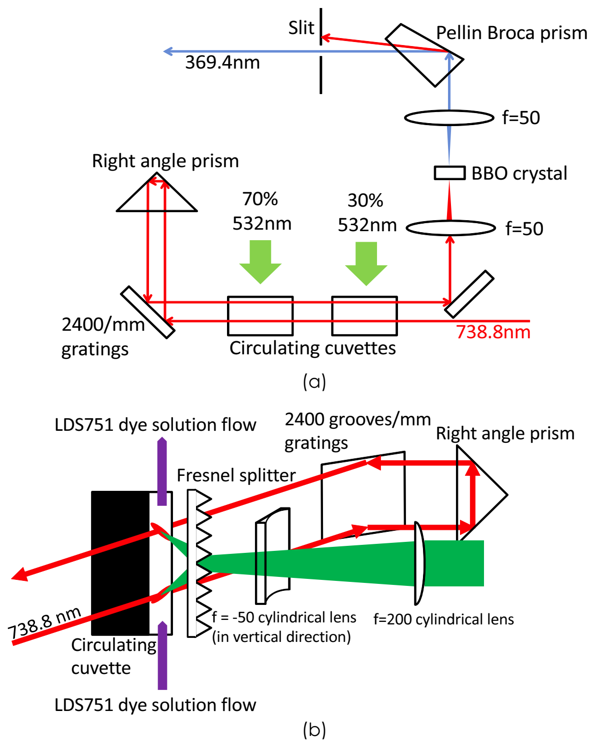

Figure 1: (Color online) Experimental setup. (a) Top view and (b) side view. Both dye cuvettes are tilted by 5° from the beam axis to prevent parasitic oscillations between the two surfaces of the cuvettes.

focal lengths of f = 300 mm and f = 50 mm are used to compensate for the vertical and horizontal beam divergence, which is typical for diode lasers. Another pair of convex lenses (f = 60 mm and f = 50 mm) forms a telescope to very slightly focus the beam (effective focal length $f \sim$1 m) so that the seed beam diameter is kept to be nearly $\sim$0.5 mm during the propagation in the four-pass amplifier. For clarity and simplicity, the optical isolator, half-mirror, and collimation lenses are not shown in Fig. 1.

The dye solution (LDS 751 dissolved in methanol at the concentration of 4.5×10^{-5} M, see Fig. 2 for the excitation and emission spectra) is circulating in the two cuvettes (25 mm length and 1 mm width), with an estimated flow rate of 2 m/s, as a result of which the fresh dye solution interacts with pump pulses. The internal pumping rate of the dye solution is 3 L/min External cooling water continuously circulates inside the dye reservoirs (not shown in Fig. 1) to dissipate the heat in dye solution so that the gain factor stays constant.

For the pump pulses we employ the second-harmonic of Q-switched Nd:YAG laser pulses (Tempest, ESI inc.), which has a 4 ns pulse duration and 30 mJ maximum pulse energy at 532 nm with a repetition rate of 1 $\sim$ 20 Hz. For our experiment, the output power is usually reduced to 10 mJ to avoid the damage on the Fresnel splitter shown in Fig. 1(b). By comparing the performance of the amplifier at various repetition rates, we have found that there is no noticeable difference in the amplified pulses if the repetition rate is lower than 20 Hz, based on which we have fixed the repetition rate at 10 Hz. The pump pulses at 532 nm are split into two by the ratio of 30:70 so that 30% of the pump pulse energy is injected into the first dye cuvette and the remaining 70% into the second. Empirically, such a splitting ratio is known to have better amplification in terms of gain and stability. Similar splitting ratio of the pump power has also been found to be efficient in single-cuvette, four-pass amplifiers [3]. Then, the pump pulses are vertically focused and horizontally expanded by the f = 200 mm and f = -50 mm cylindrical lenses, respectively.

A Fresnel splitter sheet (LPV45-0.1, Nihon Tokushu Kogaku Jushi Co. Ltd) attached to the side of the cuvettes splits the pump beam into the two parallel beams which are vertically separated by about 5 mm. The seed beam travels through the optically pumped lower areas (Fig. 1(b)) in the two dye cuvettes before it arrives at a grating with 2400 grooves/mm to suppress the parasitic ASE during the amplification. Insertion of the grating during the amplification is a commonly used technique in multi-pass pulsed dye amplifiers [2–6, 8, 9]. The diffracted seed beam is then reflected by a right-angle prism and diffracted again before it travels through the optically pumped upper areas in the two dye cuvettes. Because of the presence of the cuvette wall, the distance between the two pumped zones cannot be smaller than 5 mm. This relatively large distance, together with the large reservoir capacity and low repetition rate of 10 Hz, is helpful to prevent the bleaching of dye solution over the running time of several months. With the current circulation flux and repetition rate of pump pulses, there is no detectable temperature rise in the dye solution after a continuous running of $\sim$ 10 hours. Under the conditions described above, we have achieved the total gain of $\sim 5 \times 10^5$ in laser power by the four-pass pulsed dye amplifier. Finally, the amplified pulse is focused by a f = 50 mm spherical lens into a BBO crystal (32° cut angle, 5 mm length) for the frequency doubling.

After the frequency doubling, the amplified UV pulses at 369 nm are re-collimated by another f = 50 mm lens, and go through a Pellin Broca prism to select the UV pulses through a slit of 1 mm width. Typically 50% to 70% of the amplified pulse energy at 738.8 nm can be converted to the UV pulses. This means that up to 10 μJ pulses at the desired UV wavelength are available for spectroscopic applications, which is far more than enough for the spectroscopic study of Yb^+.

3. Results

For any spectroscopic application the laser linewidth and continuous tunability of the light source are the most important factors. Especially for dye amplifiers how much we can suppress the ASE is very crucial.

We have measured the temporal shapes of the amplified NIR pulses with a fast (bandwidth 1 GHz) photodi-

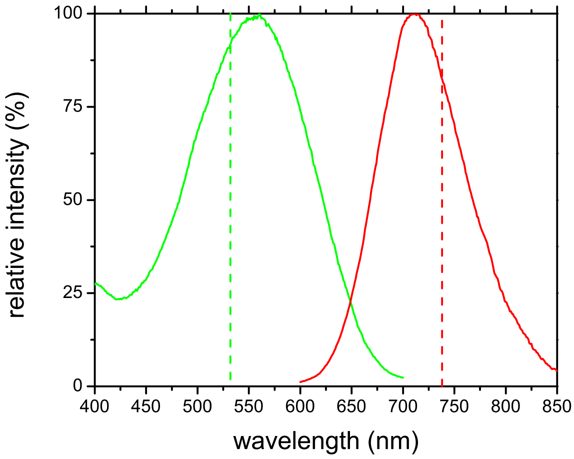

Figure 2: (Color online) Excitation (green curve) and emission (red curve) spectra of LDS 751 dye in methanol solution. The vertical green and red dashed lines stand for the wavelengths of the pump pulse and the seed laser, respectively.

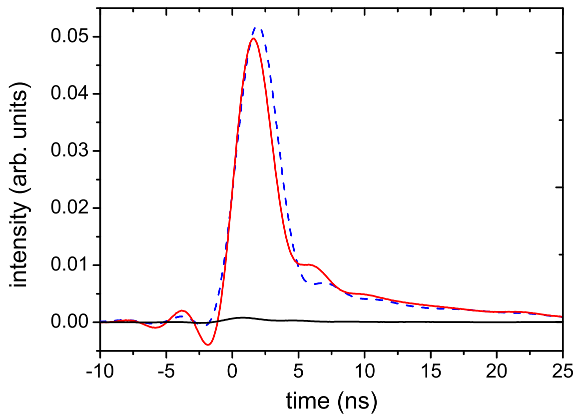

Figure 3: (Color online) Temporal shapes of the amplified NIR pulse (red curve) and the ASE (black curve). The ripples appearing around -6 to -3 ns are due to the slight mismatch of the impedances between the employed photodiode and the oscilloscope. The dashed blue curve represents the temporal shape of the pump pulse at 532 nm, which is not in the same scale with those of the former two curves.

ode, and compared its shape with that from the unseeded amplifier which contains only the ASE. The results are shown in Fig. 3. The ratio of the pulse energies between the amplified NIR pulse and the ASE is better than 20 dB, which is sufficiently good to avoid the excitation of unwanted transitions.

We have measured the linewidth and tunability of the amplified UV pulses with a confocal étalon (Coherent Model 240, with a 1 GHz free spectral range and 200 finesse). The transmission spectrum after the étalon is shown in Fig. 4(a) as a function of the read of the wavelength meter (WaveMaster, Coherent Co.) when the seed laser wavelength is scanned. Since the wavelength meter we have is for the wavelength longer than 380 nm, we cannot directly monitor the wavelength of amplified UV pulses at 369.4 nm. Alternatively we have monitored the wavelength of the NIR seed laser, which is chosen as a horizontal scale of Fig. 4(a). From Fig. 4(a), we find that the linewidth of amplified UV pulses at 369.4 nm is 230±20 MHz over the 10 GHz scanning range. Since the mean measured duration of the amplified UV pulses is 3.3 ns, we conclude that the amplified UV pulses are nearly transform-limited. The linewidth of the UV pulse can be further narrowed if longer pulses are used for pumping. We have also checked the tunability of the amplified UV pulses by continuously applying the scanning voltage on the piezo actuator of the external cavity grating inside the ECDL, which accordingly changes the lasing wavelength of the seed laser. The result is shown in Fig. 4(b). It demonstrates that we can successfully scan the wavelength of amplified NIR pulses over the 5 GHz range. The tunability range of 5 GHz for the NIR seed laser corresponds to the tunability range of 10 GHz for the amplified UV pulses, which is sufficient to resolve and identify the hyperfine transition lines of $^{170-175}\mathrm{Yb}^+$ $6s_{1/2} - 6p_{1/2}$ under natural abundances. The performance of the amplifier is stable over the continuous running time of tens of hours. However, it does require some minor maintenance typically every $\sim$ 100 hours of running time. The accumulated damage on the plastic Fresnel splitter by the pump pulses degrades the amplification a little, and therefore the splitter has to be slightly shifted by several mm to prevent the efficiency drop. Vaporization of the solvent from the cuvettes also makes it necessary to add fresh solvent into the reservoir every 2 months. If such a minor maintenance is taken care of, our dye amplifier is quite stable. Realignment of optical components becomes necessary only when the central wavelength of the ECDL is changed by large amount (such as 1 nm): Such a sudden change in the laser wavelength leads to the notable change in the tilt angle of built-in gratings in the seed ECDL, and naturally the pointing direction of the output from the LD also changes a lot.

4. Summary

We have demonstrated the generation of narrowband nanosecond laser pulses in the UV region with a continuous tunability over 10 GHz by developing a four-pass pulsed dye amplifier system with an external cavity diode laser at the NIR region as a seed laser. After the amplification we have obtained a tunable narrowband NIR pulses, which are frequency-doubled by the nonlinear crystal. We have finally obtained UV pulses at 369.4 nm with a 10 μJ pulse energy, 230±20 MHz bandwidth, and 3.3±0.2 ns pulse duration. The demonstrated tunability is as much as 10 GHz at 369.4 nm. The system we have developed requires relatively low cost and small effort for the maintenance. Such an amplifier system can be a convenient light source in the

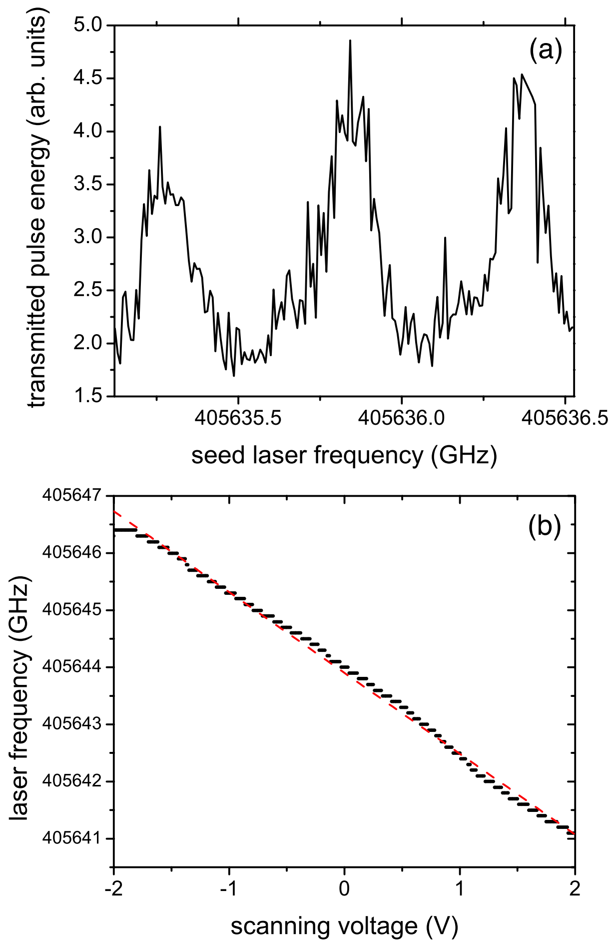

Figure 4: (Color online) (a) Transmission spectrum of the amplified NIR pulse measured with a confocal étalon as a function of the read of the wavelength meter for the seed laser. (b) Seed laser frequency as a function of scanning voltage on the piezo actuator of the external cavity grating inside the ECDL which accordingly changes the lasing wavelength of the seed laser. Note that the wavelength meter returns discrete frequency values with a 100MHz resolution, but the linear fitting of the discrete data points reveals the correlation between scanning voltage and the seed laser frequency.

UV region for various spectroscopic applications.

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